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New technologies using renewable energy in road construction

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Abstract. Energy harvesting consists in the processing and storage of energy which is normally dissipated to the ambient environment. This study presents two solutions using two methods of energy generation: conversion of solar energy into electricity on the road surface and energy recovery from road surface vibrations and displacements. The description of configuration of testing stand dedicated for road surface vibrations energy harvesting has been also included. Described testing stand will make it possible to verify the possibility of application of piezoelectric transducers in road pavement in terms of occurrence of damages and the value of generated energy.

Key words: Energy harvesting, piezoelectric, road surface.

INTRODUCTION

It seems that in case of automotive engineering, the scientists are focused mainly on the development of motor vehicles at the same time neglecting road infrastructure enabling road traffic. Currently, automotive electronic systems are in the phase of introduction of fully autonomous vehicle. The practical road tests are carried out by the automotive concerns e.g. BMW, Mercedes, Audi or Google [12, 17, 21, 35, 40]. Safety improvement is an advantage of these systems. It is possible as a result of independence from the driver’s reaction varying with the number of stimuli affecting the driver [43]. When the possibilities of standard computer systems in motor vehicles are insufficient, new systems dedicated for data acquisition and vehicle control are designed by scientists [15].

However, the development of electro-technology and data processing is weaker in the scope of road infrastructure. There are the most advanced solutions in the scope of traffic monitoring and control. The roads users can observe the lighting systems of pedestrians crossings which are supplied with solar and wind energy. However, the road surface have received insufficient attention. Here, the research works are focused on strength, durability, generated sound level, travel comfort. The present study is focused on the possibility of energy generation thanks to road pavement.

Two aspects will be presented:

– possibility to use solar energy
– possibility to use vibrations energy.

The final part presents the testing stand which is used for measurements concerning the possibility to convert mechanical vibrations energy into electrical energy.

USE OF SOLAR ENERGY

The energy of solar radiation is available practically at each point on the earth. About 50% of energy produced by the Sun is reaching the earth surface. Most often, the impact of solar energy on the earth surface is characterized by means of the following figures [28, 36]:

- Solar Constant – it is the value characterizing solar energy emitted perpendicularly per surface area unit during time unit assuming the average distance from the Sun ($W \cdot m^{-2}$). Currently, the value of 1367 $W \cdot m^{-2}$ is most often assumed as the solar constant.
- Irradiance – it is the value characterizing the total solar energy emitted during time unit per surface area unit ($W \cdot m^{-2}$). The components of irradiance are: luminous flux energy, dissipation energy and cosmic rays energy.
- Insolation – amount of energy emitted during time unit. Hour or year are most frequently used time units. The unit of insolation is $Wh \cdot m^{-2} \cdot day^{-1}$ or $Wh \cdot m^{-2} \cdot hour^{-1}$.

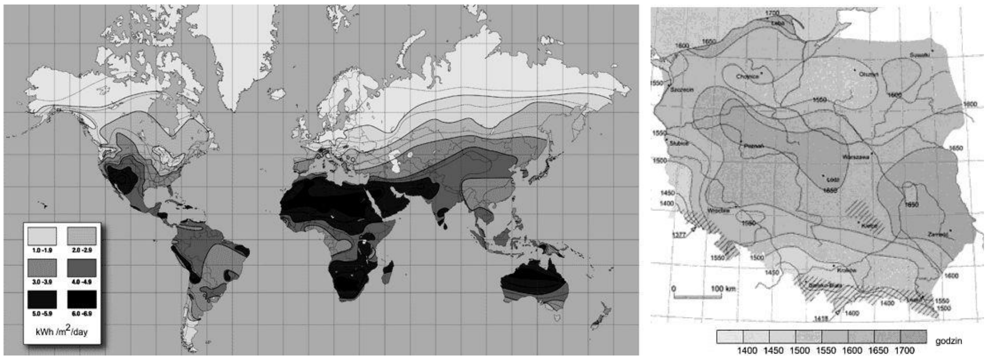

Fig. 1. Insolation on the earth (on the left) and average number of insolation hours in Poland (on the right) [27, 28, 29]

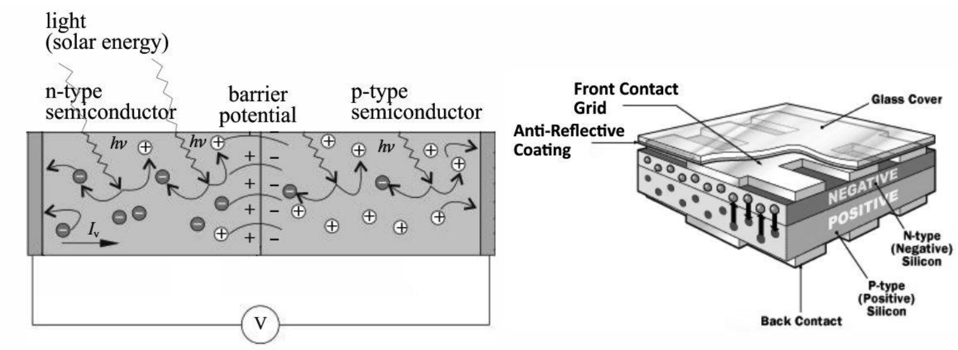

Fig. 2. Schematic structure of photovoltaic source [25]

As shown in Fig. 1, the Sun radiation is diversified geographically. The regions situated in Africa and Australia are characterized by the highest insolation. The maximum value of average annual insolation in central Australia is equal to 5,89 $kWh \cdot m^{-2} \cdot day^{-1}$. In Poland, the value of average annual insolation is five times lower [27, 28].

Two types of solar energy converters are applied. The first type of converter is a fluid or gas header. Its purpose is to convert the direct and diffusion radiation energy into fluid energy which is most often stored in a reservoir. The energy from reservoir is used for rooms heating, water preheating or in drying processes. Another type of converter is a photovoltaic cell.

Photovoltaic cells

The purpose of photovoltaic cells is to convert the solar energy into electricity. The photovoltaic phenomenon has been discovered in the year 1839 by Alexandre Edmond Becquerel [36, 39]. The conversion of solar energy into electricity in the photovoltaic source takes place in semiconductor p-n junction consisting of two areas of semiconductors (Fig. 2). One area (n type area) is characterized by doping in a manner ensuring electron excess – e.g. silicon with phosphor doping. Another semiconductor (p type area) is characterized by doping in a manner ensuring electron deficiency – e.g. silicon with boron doping. Without any additional external power supply, without any impact of luminous energy, diffusion of electron excess (-) from the *n* area to the *p* area takes place in the first phase. The holes (+) are symbolically moved in opposite direction from p to n area. This process is continued until the potential barrier is created by stationary negative ions in p area and positive ions in n area. Equilibrium state is achieved by the system. The movement of charges is slowed down by the potential barrier. Simultaneously, the charges on depletion region become the voltage source on source electrodes. As a result of supply of luminous energy to the junction, it is possible to knock out further electrons from crystal lattice and additional hole – electron pairs are generated. The potential barrier still constitutes the source of voltage (electric field). Therefore, the current will flow through the receiver and p-n junction after the receiver's connection to the source electrodes.

The structure of photovoltaic sources is diversified. The scope of most frequently specified sources encompasses the sources consisting of monocrystalline silicon, polycrystalline silicon and amorphous silicon as well as the sources consisting of semiconductor compounds. The second generation of sources is based on thin layered structures made of amorphous silicon (a-Si), Cadmium telluride (Cd-Te), copper indium diselenide (CIS). The third generation of sources is characterized by multiple layer structure, e.g. consisting of the following semiconductors: amorphous silicon or gallium arsenide [23, 25, 36, 41]. It should be also emphasized, that the works associated with implementation of perovskite solar cells with the efficiency of 3,81 % up to 22,1 % are currently in progress [4, 14, 32]. Typical efficiency of sources has been illustrated in Fig. 3.

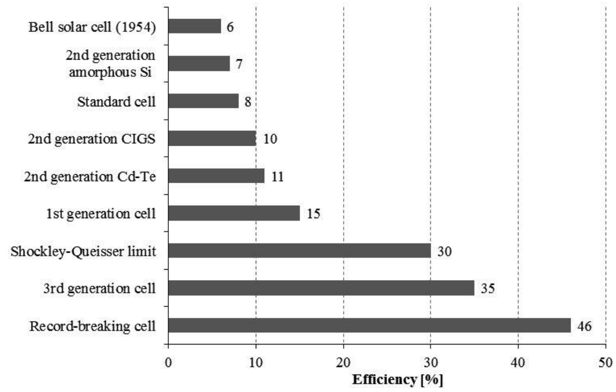

Fig. 3. Efficiencies of solar cells [41]

Photovoltaic cells in road pavement

The efficiency of typical photovoltaic cells is equal to about 15%. In case of assumed value of cells panel power of 1000 W·m^{-2}, it is possible to expect that the power generated by the panel with surface area of 1 m^2 at full insolation will be equal to 150 W. However, the ideal conditions occur during a part of day only and are extremely affected by atmospheric phenomena and cells contamination. Therefore, cells panels are arranged in groups which require significant surface areas. The roads, parking areas and yards provide surface areas which can be used for photovoltaic cells installation. Such works led to practical solutions presented below.

In the scope of introduction of new technologies of solar energy harvesting from the roads surfaces, real effects have been achieved by two organizations:

- transport infrastructure world leader – Colas with French National Institute of Solar Energy (INES) in the framework Wattway project,
- an American company- Solar Roadways Incorporated.

Wattway

Wattway project is implemented in the framework of cooperation between research institute and industrial contractor in the scope of road infrastructure including road pavements. According to the basic assumption of the project, the road surface is occupied by the vehicles during 10% of total time and can generate electricity out of this period.

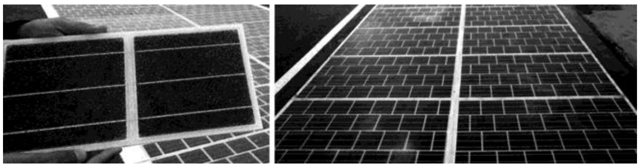

Fig. 4. View of a single photovoltaic panel and road pavement with embedded panels [7]

Features characterizing the energy generating surface:

- theoretical possibility to generate electricity for single household by the pavement surface area of 20 m^2 (excluding heating),
- possibility to place electricity generating surface onto existing pavements without any additional construction works,
- mechanical strength enabling the road surface loading with motor vehicle,
- structure not causing any slippage of vehicles,
- flexibility considering thermal changes.

It is assumed that it will be possible to extend photovoltaic panels in the form of LED diodes system. Incorporated light sources would enable the dynamic changes of horizontal marking depending on traffic intensity i.e. the changes of traffic lanes directions, changes of markings between the lanes, changes of speed limitations marking. The practical tests of Wattway panels are already in progress in the following locations [5, 6, 7]:

- Vendéspace (France, June 2016) – electric car charging station – testing surface area of 50 m^2 has been covered with 42 photovoltaic panels. The panels will generate 6300 kWh annually and will provide energy supply for electric cars batteries charging (Fig. 5);
- road RD5 (France, December 2016) – the road 1 km long covered with panels on the surface area of 2800 m^2. The energy generated on the road will be transferred to power supply grid (electricity provider Enedis). Estimated annual electricity production will be equal to 280 MWh. Estimated average daily electricity production will be equal to 767 kWh and estimated maximum electricity production will be equal to1500 kWh daily in summer period.
- testing installation of 50 m^2 of road solar panels in Georgia Visitor Information Center (West Point, USA, December 2016). Expected annual energy production is equal to 7000 kWh;
- preparation for construction of interstate road section 18 miles long - Interstate 85 in cooperation with Ray Foundation and Georgia Department of Transportation.

Fig. 5. Electric car charging station in the parking lot of Vendéspacein France (on the left); Experimental site in Georgia (United States) (on the right) [5, 6, 7]

Solar Roadways

Solar Roadways company has been established in the year 2006. The scale of its activity has been increased as a result the funds obtained from United States Department of Transportation in the years 2009 and 2011. Solar Roadways solution differs from the solution proposed by Wattway. The pavement will ensure energy harvesting but its functionality will be improved. The road is built from the beginning and consists from individual panels (Fig. 6). At the moment (March 2017), already the third prototype of road panel (SR3) has been created.

Fig. 6. Single panel from SR3 series with LED diodes (on the left); road fragment with dynamically displayed inscription [37]

Principal functions of panels creating the road pavement [34]:

- no softening in high temperatures,
- generation of electricity from solar energy,
- displaying of road lines and markings (Fig. 6),
- snow and ice removal (Fig. 7),
- modularity facilitating pavement repairs;
- no painting necessity,
- possibility of electric vehicles charging,
- water storage and transportation,
- possibility to lay additional cabling in pavement,
- technology development in an easy manner.

Fig. 7. Modular pavement consisting of SR3 panels (on the left); snow removal through panel preheating (on the right) [31]

The functionality of Solar Roadways pavement is wider than possibilities of Wattway pavement. The panels are provided with integrated electronic system controlling the lighting and heating elements operation, used for traffic monitoring and electric cars loading.

However, this solution is still in practical tests phase. In practice, Solar Roadways pavement is used in the form of a small parking place only (Fig. 8). Thanks to the funds from United States Department of Transportation we can hope that it will be possible for the project to reach the phase of practical road tests or to demonstrate that the proposed solution is too expensive and unfeasible in a larger scale.

Fig. 8. Individual small solar parking lot [3]

USE OF MECHANICAL ENERGY

Piezoelectrics

Piezoelectrics are the materials characterized by properties stated in the year 1880 by brothers Pierre and Jacques Curie. Piezoelectric phenomenon consists in generation of electric charges on the surface of piezoelectric materials under the influence of an external force (stress) e.g. compressive, tensile or bending stresses. Distribution of electric charges is uniform in piezoelectric not subjected to external forces and this material remains electrically neutral (Fig. 9a). As a result of a force applied to piezoelectric material, the positions of electric charges to each other will change and electric charge will occur on the material surface (Fig. 9b). The value of generated electric charge or electric voltage is a measurable effect of applied force (stress) [1, 10, 11].

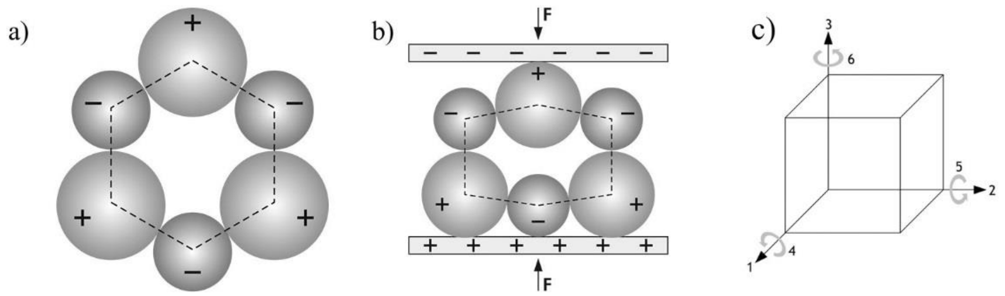

Fig. 9. Mechanism of piezoelectric phenomenon [1], c) determination of piezoelectric crystal axes [9]

Piezoelectric effect can be described by means of coupled equations considering stresses, strains, electric charge and electric field [9, 11, 16]:

$$S_{ij} = s^{E}_{ijkl} T_{kl} + d_{kij} E_k \; , \quad (1)$$

$$D_j = d_{jkl} T_{kl} + \varepsilon^{T}_{jk} E_k \; , \quad (2)$$

where:

S_{ij} – mechanical strain,

s^{E}_{ijkl} – mechanical compliance of the material,

T_{kl} - mechanical stress,

d_{jkl} - piezoelectric coefficient for the piezoelectric effect (matrix); d_{kij}- piezoelectric coefficient for the piezoelectric effect (transposed matrix d_{jkl}),

E_k – electric field strength,

D_j – electric charge density displacement (electric displacement),

ε_{jk} - electric permittivity (dielectric constant),

The subscripts *ijkl* indicate the direction of stress *T* and electric field *E* (Fig. 9c),

The superscript *E* indicates a zero or value of electric field,

The superscript *T* indicates a zero or value of stress field.

The direct piezoelectric effect, when piezoelectric material can generate a voltage during deformation, is described in the second equation. The electric charge density displacement field (D) is the source of electrical charges, and further the electrical energy that can be obtained from the piezoelectric. The first equation refers to the opposite effect - converse piezoelectric effect, where the application of an electrical field creates mechanical deformation in the piezoelectric.

Table 1 contains the parameters of piezoelectrics which are the most popular materials currently:

– PZT (lead zirconate titanate),
– PVDF (polyvinylidene fluoride),
– PMN-PT (lead-magnesium-niobate lead-titanate).

Table 1. Selected properties of piezoelectric materials [24, 42]

Properties	PVDF [42]	PZT [42]	PZT-5A [24]	PZT-5H [24]	PMN-PT [24]	PMN-PT [42]
Density [kg·m^{-3}]	1,78	7,60	7,75	7,5	8,00	8,20
Relative dielectric constant ($\varepsilon/\varepsilon_0$) [-]	12	1700	1600	3400	>5000	4400
Piezoelectric strain constant d_{33} [10^{-12} C·N^{-1}]	30	360	374	359	>2200	>1700
Electro-mechanical coupling coefficient k_{33} [-]	0,11	0,69	0,71	0,75	0,93	>0,9

The piezoelectric materials are characterized by low resistance to high strains. They are applied in various fields e.g. automotive industry (airbags sensors, alarm systems loudspeakers , fuel injectors etc.), hardware (e.g. in ink printers), popular electronic equipment (e.g. lighters, air humidifiers, loudspeakers), medical equipment (patients monitoring, ultrasonography), military equipment (e.g. depth sensors, sonars, guidance systems), measuring technique (e.g. for monitoring and compensation of structural elements vibrations in structures, vehicles, aircrafts). „The piezoelectric strain constant" (Tab.1) is the best illustration of the possibility of electric charge generation under the influence of external forces. Selected examples of works associated with generation of energy which can be used to provide power supply for other equipment are presented below.

– MEMS (Micro-Electro-Mechanical Systems) are integrated measuring – actuating systems characterized by compact structure and small dimensions. Therefore they are equipped with their own energy sources. AlN, ZnO, PZT, PMN-33%PT piezoelectric layers dedicated for MEMS systems power supply are developed by a scientists group from the School of Mechanical and Materials Engineering (Washington State University). According to their publication, obtained actual voltage was about two times lower than the voltage resulting from system functioning simulation [2].

– The possibility of batteries charging by means of piezoelectric sources was tested by a scientists group from Michigan Technological University, Virginia Polytechnic Institute and State University and Los Alamos National Laboratory. In their research, they practically determined the times of charging for batteries with selected capacities by means of three selected piezoelectrics. For example, the time of charging for battery with capacity of 300 mAh was equal to 6–22 hours depending on applied piezoelectric and type of vibration [33].
– The possibility of the equipment power supply by means of piezoelectric generator installed in boot sole was practically tested by the scientists from Massachusetts Institute of Technology. In theory, a person weighing 68 kg and making 2 steps per second and lifting the heel to the height of 5 cm should be able to generate 68 W. PVDF piezoelectric generated peak power of up to 20 mW and PZT generated peak power of up to 80 mW. It has been assumed that the effective power is equal to about 1 mW in case of PVDF and to about 2 mW in case of PZT [22].

Energy harvesting from roadway – test stand

As in the case of piezoelectrics use for the conversion of mechanical energy of the movement of human body, equipment and building into electricity, research works have been commenced in the scope of potential use of vibration and strains energy on the roads and walkways. There are some commercial products e.g. the solutions of Waynergy, Pavegen companies [8, 26]. However, their use is limited owing to the costs and value of generated energy. However, the authors of these solution have informed that it is possible to generate the energy of a few watts (W) e.g. 7 W - paving unit 600 x 450 x 82 mm (Pavegen Company), 4 W – per step (Waynergy Floor),0,1W per step (Power Generating) [8, 26]. Review studies in the scope of energy conversion by means of piezoelectrics indicate the possibility of power supply from single transducer between 1 and 500 mW [13, 19, 38]. The values exceeding 1 W are specified in the studies describing mathematical modelling of phenomenon or assuming that a constant part of object energy is converted. In practice, energy transfer process directly to the piezoelectric transducer is disturbed by its installation method and the occurrence of stimulation frequencies other than assumed ones.

Owing to the following factors:

– significant discrepancy between results of simulation, laboratory tests and in-situ tests,
– lack of published results of practical tests of road piezoelectric sensors loaded by means of motor vehicles;
– development of piezoelectric materials leading to better parameters of the conversion of mechanical energy into electricity, the scientists have designed and commenced the works associated with energy harvesting from roads pavements equipped with piezoelectric transducers.

Road pavement consists of several courses presented in Fig. 10. Hot-mix asphalt (HMA) is the most popular material used for roads construction. There are 6 traffic categories depending on road traffic load. The traffic category is characterized by means of loading axles number. The loading axle is equal to 100 kN. Specified 6 traffic categories are [20]: KR1 - 0÷12 axles, KR2 - 13÷70 axles, KR3 - 71÷335 axles, KR4 - 336÷1000 axles, KR5 - 1001÷2000 axles, KR6 ≥ 2001 axles.

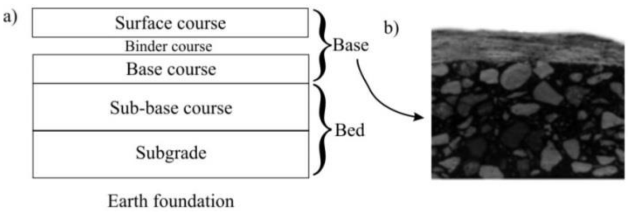

Fig. 10. a) Road surfaces; b) Cross section through base layer

Hot-mix asphalt (HMA) recipes have been prepared for each road traffic category. Each bed will be provided with piezoelectric transducers with spacing of 5 mm from top pavement course. It is planned that piezoelectric transducers will be arranged in binder course as well as in surface course. The samples will be prepared in the form of slabs. Electromechanical slab compactor PAVELAB 77-PV40B05 will be used for samples preparation [Fig. 11]. The compactor provides a compacting system with a 535 mm radius roller segment head. The roller segment moves freely by simple friction for improved compaction uniformity. A stepper motor moves the roller segment vertically under displacement and load control. Electromechanical slab compactor PAVELAB 77-PV40B05can compact asphalt slabs to a target density at specific loads corresponding to those of pavements rollers used in road construction. HMA slabs equipped with piezoelectric transducers will be tested during wheel tracking tests.

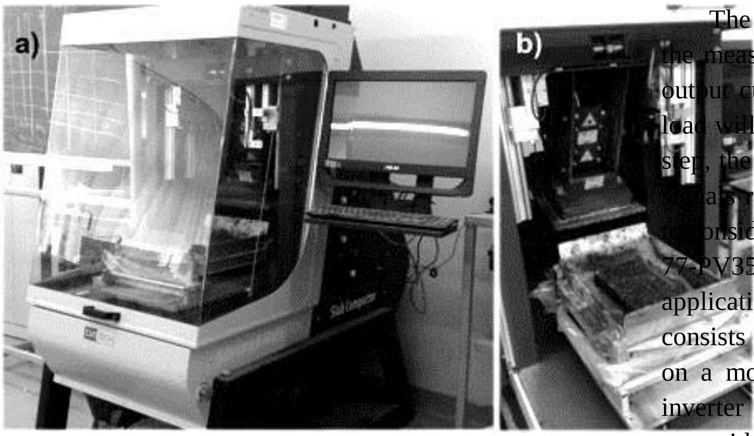

Fig. 11. PAVELAB electromechanical slab compactor 77-PV40B05: a) general view of compactor; b) form for the preparation of slab samples

PPA-1001 and PPA-1011 piezoelectric transducers supplied by Midé company will be used for tests. This type of piezoelectric transducers has been selected owing to their low resonance frequency. Selected parameters of PPA-1001and PPA-1011 piezoelectric transducers are specified in Tab. 2.

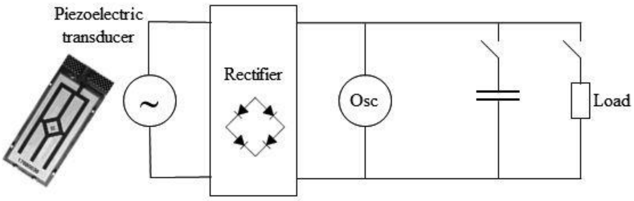

Fig. 12. Diagram of the measuring system

The transducer embedded in slab will be connected to the measuring system presented in Fig. 12. The shape of output curve of transducer and output power at resistive load will be recorded in the first phase of tests. In the next step, the system will be extended by the system of output signals recording in the period of 24 hours. It is planned to consider the impact of load type on output power [18]. 77-PV3502 single wheel tracker will be used for load application (Fig. 13). The wheel tracking apparatus consists of a loaded wheel, which bears on a sample held on a moving table. The test speed can be adjusted by inverter control. The wheel is fitted with a solid rubber tyre with an outside diameter of 200 mm. The wheel load under standard conditions is 700 ±10 N. The wheel tracker is fitted with a temperature controlled cabinet with a temperature range from ambient to 65°C ±1.0° C. Deformation and sample temperature are recorded by the internal data acquisition and control system and transmitted to the acquisition software.

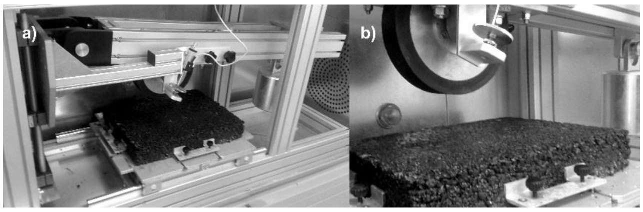

Fig. 13. Single wheel tracker 77-PV3502: a) general view of cabinet; b) sample inside wheel tracker

Table 2. Selected properties of piezoelectric transducers [30]

Property	PPA-1001	PPA-1011
Length / Width/ Thickness [mm]	54.4 / 22.4 / 0.48	71.0 / 25.4 / 0.71
Piezo Length / Width/ Thickness [mm]	46.0 / 20.8 /0.18	46.0 / 20.8 /0.18
Number of Piezo Layers [-]	1	1
Piezo Materials	PZT-5H	PZT-5H
Capacitance [nF]	100	97
Mass [g]	2.8	3.0

CONCLUSIONS

Efficient energy use is based on the equipment switching on and off in an intelligent manner. Minimization of expenditures is based on the use of renewable energy sources e.g. wind, solar and water energy. Technologies determined as energy harvesting consist in the processing and storage of energy which is normally dissipated to the ambient environment. The roads can become the sources of “cheap” energy owing to their large surface area and common occurrence.

This study presents two solutions using two methods of energy generation: conversion of solar energy into electricity on the road surface and energy recovery from road surface vibrations and displacements. The description of configuration of the testing stand dedicated to road surface vibrations energy harvesting has also been included. The following works in the scope of vibration energy harvesting are in progress:

1. Extensive research in the scope of piezoelectric materials parameters.

2. Simulation tests in the scope of vibration energy conversion into electricity are continued with optimistic results not confirmed in practice.
3. Tests in the scope of energy harvesting from piezoelectric transducers focused on the transducers functioning.
4. Limited tests in the scope of practical use of piezoelectric transducers on real objects.

The presented testing stand:

1. Makes it possible to prepare real samples of road pavement with piezoelectric transducers embedded inside.
2. Makes it possible to carry out the tests of energy generation by means of piezoelectric materials under a programmed load of the pavement.
3. Will make it possible to verify the possibility of application of piezoelectric transducers in road pavement in terms of occurrence of damages and the value of generated energy.

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